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TITLE: De-noising of ECG signal on FPGA platform using digital filters

Short Synopsis

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Abstract

High frequency muscular contraction noise and power line interference removal from Electrocardiogram (ECG) is a problem which distorts the QRS segment of the ECG signal. Reducing noise from the biomedical signal is still a challenging task and rapidly expanding field with a large range of applications in ECG noise reduction. The QRS complex of the ECG signal represents the ventricular contractions and R peak indicates a heartbeat. This QRS segment is very important and has significant information related to abnormalities of the heart. The most common method of removing these noises is low pass filtering. Compared to microcontroller, DSP based medical kit and application specific integrated circuits (ASICs), field programmable gate arrays (FPGA), owing to their low cost and reconfigurable property, have a low time to market. This work proposes an approach to design and implement digital filter algorithms based on FPGA. Higher sampling rate is the advantages of FPGA approach to digital filter implementation than are available from traditional DSP chips, lower cost than ASIC for moderate volume application.

Digital filter is the preeminent solution that caters to noise reduction up to a satisfactory level. This research work will be based on low pass filtering of ECG signal. Different Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) filters are to be designed using MATLAB in order to check the feasibility of the specifications. Digital filters shall be designed in MATLAB to denoise the ECG signal with muscular noise and the performance will be evaluated based on error, accuracy and signal to noise ratio (SNR). Further the filters with the desired specifications are to be designed using Verilog Hardware Description Language (HDL). Simulation of the algorithms shall be done using MODELSIM 6.4a simulator for verifying the functionality of these designs and the architecture shall be implemented in Xilinx Spartan 6 FPGA. The Verilog simulation results of IIR and FIR filters are expected to give reliable the filtering functions matching with MATLAB design of the filters. The speed, power and area of the implemented algorithms shall be analyzed. The proposed FPGA based low cost ECG system will operate with high reliability, better performance and low maintenance.

Keywords: ECG signal, Digital filters, Matlab, Verilog, Modelsim, FPGA

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Introduction

Human body constitutes of many organ systems: it includes the nervous system, the cardiovascular system and the musculoskeletal system, with others. Each system consists of specialized cells which perform the function specific to it. For example, the circulatory system performs the vital task of rhythmic pumping of blood throughout the body to facilitate the delivery of nutrients and oxygen as well as pumping blood through the pulmonary system for oxygenation of the blood itself. These physiological processes are complex phenomena as well as nervous or hormonal stimulation and control. The inputs and outputs could be in the form of physical material, neurotransmitters, or informational; and the action could be mechanical, electrical, or biochemical. Most physiological processes are accompanied by or evident themselves as signals that reflect their nature and activities. Such signals could be biochemical in the form of hormones and neurotransmitters; electrical in the form of potential or current and physical in the form of pressure or temperature. Biomedical signal processing and pattern analysis techniques for effective non-invasive diagnosis during online monitoring of patients are few area of research in the field of signal processing. This is the fastest growing technique and widely accepted because of its safety features, quick and harmless nature.

An electrocardiogram (ECG) is a test that checks the electrical activity of heart and it needs to be processed before analysis. The objective of ECG signal analysis is QRS detection and to determine the instantaneous heart rate. The ECG signal determines the rate and pattern of the heartbeat and provide indirect evidence of blood flow to the heart muscle. Since the ECG signal is sometimes recorded during the course of physical exercise, there is all likelihood that the signals gets corrupted due to some other physiological processes of the body and get contaminated by noise.

There are different methods to remove the noise of the ECG signal which may include digital filters like IIR or FIR filter. Each has its own advantages and disadvantages. FIR filter is always stable but it needs larger memory space to store its larger coefficients. Also it has linear phase characteristic. On the other hand the IIR filter can be unstable sometimes due to feedback loop and has less number of coefficients. Hence, it is necessary to have knowledge regarding the filter properties and design criteria to choose the proper filter for a particular application. Many researchers have worked on various filters de-noising algorithms with an objective to remove the aforesaid noises. Various filtration techniques such as low pass filter,

high pass filter, band pass filter and notch filters are used for preprocessing of signals for further ECG signal analysis.

Many developments in the medical system technology gave birth to monitoring system based on Programmable Logic Devices (PLDs). Although not new to the realm of such devices, field programmable gate arrays (FPGAs) are becoming increasingly popular for rapid prototyping of designs with the aid of software simulation and synthesis. Software synthesis tools translate high level language descriptions of the implementation into formats which is compatible with FPGA. The rising number of design changes through software synthesis becomes more cost effective than similar changes done for hardware prototypes. It is well known that FPGAs are widely used in the implementation of fast digital systems for retrieval, processing, storage and transmission of data. Xilinx, Altera, Actel, Quick logic are some of the companies making FPGA in the world. Verilog and Very High Speed Integrated Circuit HDL (VHDL) are hardware description language to design digital logic using FPGAs and CPLDs. FPGA provides optimal device utilization through conservation of board space and system power hence reducing the complexity of the system.

As the complexity of the system increases, the system reliability decreases and the hardware platform do not guarantee the reliability typically quantified in mean time between failures (MTBF) calculations. System reliability is increasingly determined by hardware and software architecture, development and verification processes, and the level of design maintainability. Currently, the primary reason most engineers choose FPGAs over DSP is driven by the application of MIPS (millions instruction per second) requirement along with the inherent advantage of reliability and maintainability.

The objective of this research is to successfully denoise ECG signal on FPGA platform by applying different IIR and FIR filters. The algorithm will be analyzing the component of the ECG signals to retain the clinical information. At last for evaluating the system, compare the FPGA results with the results obtained from analyzing the signals by MATLAB.

Literature Review

The continuous research has led to many new developments in design and development of acquisition of ECG signal monitoring system and denoising of ECG signal. Bansal et. al., (2008) developed a prototype ECG system which is consists of front end amplifier, right leg drive to improve CMRR, DC restoration circuit and analog filter using TL084C IC [2]. Bansal et. al., (2009) developed data acquisition and wireless transmission system for carotid pulse wave in real time and viewed it using virtual oscilloscope via various communication ports [3]. Further Bansal and Singh (2014) also developed a dual channel acquisition system for online detection of heart rate variability from real time acquired ECG and carotid waveforms of human simultaneously using algorithm in MATLAB [5].

Research on design and development of ECG monitoring system with economic viability and technical feasibility has been an ongoing endeavor by researchers in the field of biomedical engineering. In order to bring down the cost, Ravikumar (2012) integrated FPGA chip into an ECG monitoring system to collect, store and playback simultaneously along with wireless transmission [29]. A compact computer based device for doctors to acquire real time ECG signal has been designed by Bansal (2013) using various 50 Hz active notch-filter topologies in P-spice [4]. Martini et.al. (2010) explored an adaptive filtering technique which removed a large amount of motion artefacts and decreased beat detection errors [24]. Kumar and Malik (2010) carried out off-line evaluation of ECG signal using spectrogram and power spectral density to find the minute abnormalities of ECG signal [21]. Alfaouri and Daqrouq (2008) successfully implemented analytical techniques to determine and evaluate the legal accuracy range of ECG signal for detection, filtration and compression [1]. Chan (2010) suggested the use of signal averaging to produce a readable ECG by increasing the resolutions. Here various physiological features are still intact and can be interpreted which are otherwise difficult from the raw ECG data that are to be explored [7]. Although Fourier transform are the best tool to analyze the frequency component of the signal but it has its own limitation. Singh and Tiwari (2006) used a procedure of mother wavelet basis functions for denoising of the ECG signal in wavelet domain and retained the necessary diagnostics information contained in the original ECG signal [31]. Kozaitis (2008) used a third-order, correlation-based method to remove noise from ECG signal for identifying features in ECG signal and he proved that this is better method than a conventional second-order wavelet-based method [19]. Dliou et al., (2013) proposed a method for analyzing a noised ECG signal to diagnose cardiac arrhythmia which is combination of the empirical mode decomposition and the Choi-Williams time-frequency techniques. Their work

divided in two parts. In the first part they applied EMD method to filter the noised abnormal ECG signal and in the second part applied Choi-Williams time frequency technique to extract the QRS complexes to detect abnormality present in the ECG signal [10]. Hang and Liu (2011) used ensemble empirical mode decomposition algorithm for filtering of Guassian noise in ECG signal. Also used partial reconstruction of intrinsic mode function as a filter for the same [8]. Barick and Bagha (2013) rightly illustrated the effect of the discrete wavelet transform considering two synthesis parameters MSE and SNR, showing the improved quality reconstruction of ECG signal for better clinical diagnosis [6]. Pratap et al., (2013); Mbachu et al., (2011) showed pre-processing of ECG signal by FIR filter using different window techniques [27, 25]. Sastry et al., (2012) presented designing of FIR filter using different existing windows to remove power line interferences 60Hz of ECG signal and compared with a proposed window gave a better result in terms of SNR [30]. Dey et al., (2011) suggested an efficient analytical tool which allowed to increase signal to noise ratio by using Functional Link Artificial Neural Network for the denoising of the ECG signal [9]. Joshi et al., (2013) used moving averaging filter for de-noising and smoothing out the ECG waveform and suppressing 50 Hz power line noise but quiet unsuccessful in clearing the baseline wandering. But using it in combination with a band pass filter cleared the noise along with the baseline wandering [14]. Previous studies by Kumar et al., (2012); Singh and Yadav (2010) applied digital filtering methods to cope with the noise artifacts in ECG signals [20, 32]. Mihov (2013) proposed filters which are built by summarizing two partial simple moving averaging filters using MATLAB environment [26]. Rastogi and Mehra (2013) proposed a hybrid technique by merging Daubechies wavelet decomposition and different thresholding techniques using Butterworth or Chebyshev filter. The result has been assessed based on minimum mean squared error, high signal to interference ratio and peak signal to noise ratio using wavelet and signal processing toolbox in MATLAB [28]. Leelakrishna and Selvakumar (2013) removed EMG signal from ECG signal using high speed FIR low pass filter with an efficient design and low cost hardware devices [22]. Joy and Manimegalai (2013) used wavelet transform and proposed improved thresholding to remove the EMG noise from ECG signal. This method preserves the characteristics of the original ECG signal [15]. Jha et al., (2014) suggested a technique for denoising of the ECG signal based on the empirical mode decomposition which is suitable for any non-stationary signal due to its data driven and adaptive nature. They have been removed the high frequency noises that includes electromyogram, motion artefacts and white Gaussian noises [13]. Kaur et al., (2011) proved IIR zero phase filtering as an efficient method for the removal of baseline wandering from ECG signal [17]. Tarek et al., (2012) found that Sgolay

filter is the best method for de-noising ECG signal compared to Notch filter and Wavelet filter [33]. Gupta and Chand (2012) proposed wavelet filter design for de-noising ECG signal because of Butterworth low pass filter for being less applicability for its distorted response [12]. Luo and Johnston (2010) suggested some proposals to improve and update existing ECG data pre-processing standards and guidelines [23]. Literature therefore suggests that detailed analysis of algorithms for de-noising ECG signal using different filters need to be explored. Elmansouri et. al., (2013) proposed Undecimated Wavelet Transform (UWT) method to realize a de-noising digital electronic circuit on the Field Programmable Gate Array (FPGA) [11]. Kansal et.al., (2011) designed and implemented digital filter algorithms based on Field Programmable Gate Arrays (FPGAs) and verified the design and results that comes from the hardware [18]. Ravikumar (2012) carried out filtering with low pass FIR architecture and implemented in VHDL on FPGA platform [29]. Vijaya et. al., (2012) designed the pan and Tompkins QRS detection algorithm and low power architecture to implement on FPGA [34]. Kale et. al., (2011) proposed a method to measure SpO_2 and designed Universal Asynchronous Receiver Transmitter using VHDL and implemented on Xilinx FPGA [16]. The Modelsim Xilinx Edition and Xilinx Integrated Software Environment used for simulation and synthesis respectively and the Xilinx Spartan 3 Family FPGA development board used for implementation.

Gaps in Literature

Research is being carried out in the field of medical technology for development of better and cost effective ECG monitoring system. Noise produced in ECG signal mainly stems from biological and environmental sources. For effectively reducing the noise in ECG analysis, several techniques are available in the literature of digital filtering for pre-processing of the ECG signal. Most types of interference that affect ECG signals may be removed by digital filters but the discouraging part is all digital filter do not give similar results, since the filtering methods depends on the types of noise in ECG signal.

Most of the research has successfully implemented FIR filtering system and performance evaluation is done for different filtering techniques. Similarly separate work on IIR filtering system and their performance evaluation is also carried out by few researchers. However the algorithm published requires large memory space and are heavily processor demanding, therefore do not allow successful real-time operation on PC. Significant research and industrial attention is being given to health care system based on autonomous ultra-low-power devices capable of performing real time sampling and signal processing like PLDs and FPGAs. This work focuses on denoising of ECG signal in FPGA platform because of its high throughput, low prices, and

flexibility of design, testing and rapid prototyping, reliability and maintainability. Therefore, there is a huge emphasis to implement bulk of the software algorithm for biomedical signal processing in FPGA technology. Moreover the use of digital signal processors was nearly ubiquitous in the past, but with the changing needs of many applications outstripping the processing capabilities of digital signal processors (measured in MIPS), the use of FPGA is growing rapidly and the primary reason most researchers prefer to use FPGA over a DSP.

Description of Broad Area

An electrocardiogram is a display of the electrical activity of the heart (cardiac) muscle as obtained from the surface of the skin. As the heart performs its function of pumping blood through the circulatory system, resulted action potentials responsible for the mechanical events within the heart is a certain sequence of electrical events. In the resting state, cardiac muscle cells polarized with the interior of cell negatively charged with respect to its surroundings. The charge is created by different concentrations of ions such potassium and sodium on either side of the cell membrane. In response to certain stimuli, movement of these ions occurs, particularly a rapid inward movement of sodium this process is known as depolarization, rapid loss of internal negative potential results in an electrical signal. The mechanism of cell depolarization and repolarization is used by nerve cells to carry impulses and by muscle cells for triggering mechanical contractions. Figure 1 & 2 shows the nerve control of the heart and typical ECG waveform.

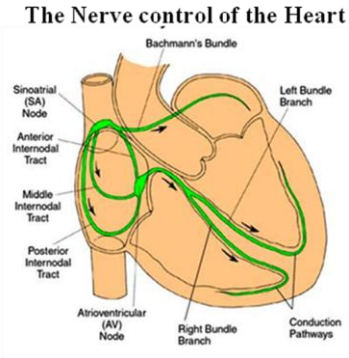

Figure 1 Human heart

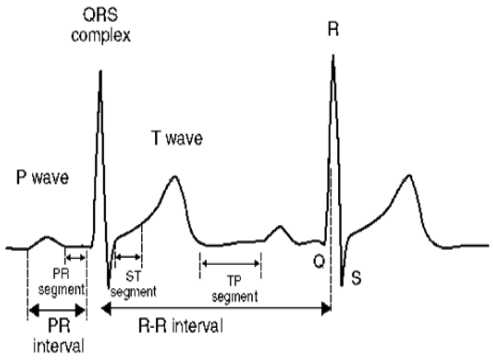

Figure 2 Typical ECG signal

There are certain cells in the heart which are capable of spontaneous depolarization. These cells are important in the generation of heart rhythm and exist in the sinoatrial (SA) node of the heart. They set the heart rate by depolarizing most rapidly. Depolarization of the SA

muscles causes them to contract and pump blood into the ventricles before repolarising. The electrical signal then passes into the antrio ventricular (AV) node and causes the ventricles to contract and pump blood into the pulmonary and systematic circulation.

The ventricle muscles then re-polarize and the whole process repeats when the pacemaker cells in the SA node depolarize again. Figure 2 shows a typical ECG signal. P-wave is due to depolarization of the atria, QRS is due to depolarization of the ventricles and the T-wave is due to repolarisation of the ventricles. Analysis of these in details permit diagnosis of a wide range of heart conditions. It is used to evaluate the heart rhythm, diagnose poor blood flow to the heart muscle (ischemia), diagnose a heart attack, and diagnose abnormalities of the heart such as heart chamber enlargement and abnormal electrical conduction. A single cardiac cycle is projected to produce one heartbeat. Deflections above or below the isoelectric line are called waves. Each wave is labeled with a letter. The waves are called the P wave. QRS complex, and the T wave, as shown in Figure 2 which also shows some important intervals related to ECG.

The size of the waves and particular time intervals give significant information. For example the duration of a normal "P" wave should be between 0.08 and 0.1 seconds; an increased width of "P" wave may be a sign of left atrial abnormality or right atrial hypertrophy (enlargement) and a taller "P" wave may point to that atrial enlargement has occurred due to hypertension, coronary pulmonale, or congenital heart disease. Similarly, when a patient has acute myocardial infarction, the S-T segment is elevated. When the heart muscle does not receive enough oxygen, depressed the S-T segment.

The electrocardiogram (ECG) is a 1-D signal as time varies signal reflects by the ionic current flow which causes to make heartbeats by means of contraction and relaxation of heart muscles. These signals obtained by recording the potential difference between two electrodes placed on pulsating area of the skin and require critical signal processing. A feature extraction with precise computation is always a challenging task. For the correct diagnosis of the heart the ECG signal should be free from the noise. While ECG signal is corrupted by various kinds of noise like baseline noises, power line interference, electrode contact noise, motion artifacts, instrumentation noise generated by electronic devices, electrosurgical noise etc. It is necessary to remove these noises from the signal for further processing and analysis. There are various methods to remove the noise of the ECG signal which may involve the IIR or FIR filter along with their advantages and disadvantages. Filter properties, design criteria and the applications are the important parameters used to decide which filter to choose.

Digital filter is the preeminent solution that caters the noise reduction up to satisfactory level and is best suited for ECG analysis by improving the quality of ECG signal.

Since the electrocardiogram lacks flexibility and neither it is compatible with the PC and communications standards nor can it be easily upgraded, therefore emphasis on designing systems with embedded circuits and available technologies to design a flexible electrocardiogram system with an improved filtering algorithms. Reducing noise from the biomedical signal is still a challenging task and rapidly expanding field with a wide range of applications in ECG noise reduction.

In today's scenario computer and electronics world need a reconfiguration facility because of cost effective approach. There are two different ways of performing computations one is hardware based which is having e-waste after damaging and second is software based which gives simulation results. Software computing provides flexibility to change applications on a fly and perform a variety of tasks. Innovative devices such as field programmable gate arrays (FPGAs) combine the benefits of software and hardware. An FPGA based system can be reprogrammed many times because computations are programmed into the chips, but they are not permanently frozen at a time of manufacturing process.

Problem Identification

- Medical monitoring devices are more sensitive for biomedical signal recording and need more accurate results for diagnosis. Accurate diagnosis of the patient from the result from biomedical signal recording is difficult with the help of medical monitoring equipment such as ECG.
- ECG instruments are quiet bulky having multiple sensors and too many wires between the sensors and monitor devices, which limits the patients activity and comfort level. It is expensive and complicated for self examination. Available systems require common communication port to interface any output display device.
- ECG signals obtained are frequently corrupted with different electrical and mechanical noises such as power line interference, electrode movement, motion artefacts, baseline

drift, instrumentation noise generated by electronic devices, white noise etc. Such unwanted disruption into the ECG signals makes the interpretation a tedious task for doctors. Hence for any clinical application a noise free ECG signal is a primary requirement for a cardiologist to provide appropriate and adequate treatment for any heart ailing patients.

- Due to non-stationary characteristics of ECG signal, it is very complex to analyze it visually. Therefore there is a requirement for computer based methods for analysis of ECG signal which is reliable for the diagnosis of cardiovascular diseases.
- Implementation of digital filters algorithms on single-chip, DSP and programmable logic devices are slow, sluggish and non flexible compared to the FPGA. Implementing them using FPGA has the characteristic of the real-time, high flexibility, faster processing speed and low production cost.

Objectives of the research

- To do extensive literature survey in the proposed area of research
- To design algorithms for IIR and FIR filters in Matlab environment to denoise ECG signal
- To test the designed algorithms on Modelsim
- To transfer digital filter algorithm on FPGA plateform
- To analyze the complexity and accuracy of digital filters

Research Methodology

In the present work, various ECG de-noising algorithms using FIR and IIR filters are to be developed to remove high frequency noise with the help of MATLAB (R2011a). An ECG data sample from the directory of Physionet MIT-BIH Arrhythmia database is to be chosen and it will be corrupted by adding artificial noise. The filter algorithms are to be designed and compared statistically in terms of signal to noise ratio, error and accuracy.

Matlab code of digital filters shall be converted into Verilog hardware description language and then simulated in Modelsim Altera 6.4a simulator. Finally the algorithms will be implemented on Sparton 6 FPGA. Block diagram of implementation of filter algorithms on FPGA is shown in Figure 3.

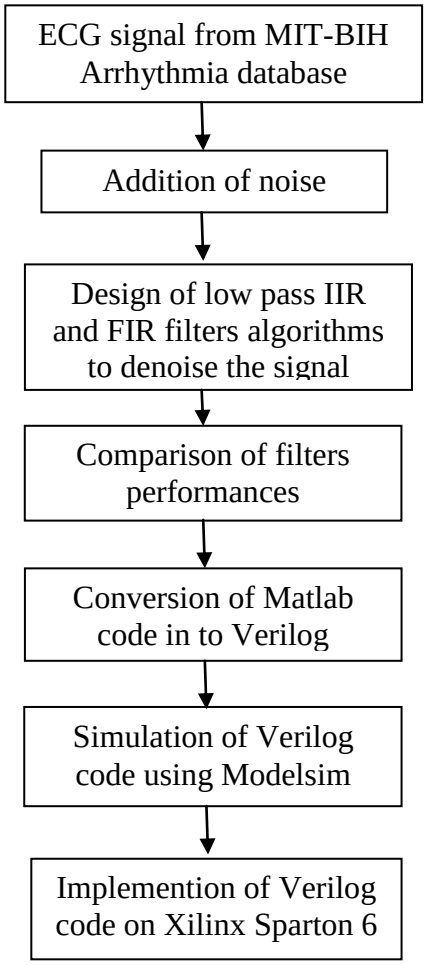
ECG signal from MIT-BIH Arrhythmia database
Addition of noise
Design of low pass IIR and FIR filters algorithms to denoise the signal
Comparison of filters performances
Conversion of Matlab code in to Verilog
Simulation of Verilog code using Modelsim
Implemention of Verilog code on Xilinx Sparton 6

Figure 3 Block diagram for implementation of filter algorithms on FPGA

Proposed outcome of the research

It is proposed that the following targets may be achieved from this research

- The output ECG signal obtained from the various digital filters would be compared statistically in a noisy environment under various levels of noise. The effect of order of digital filters will also be studied on the performance of output signal.

- The above digital filters are to be designed in Matlab and the designed filters are to be converted into Verilog and exported to Modelsim environment for the implementation

on hardware.

- The above Verilog code will be implemented on Xilinx Sparton 6 FPGA for hardware implementation.

- The complexities of the implemented circuit on FPGA, in terms of (No of adders, multipliers etc.) will be compared with that of implemented in Matlab.

- A methodology has to be developed to transfer any tested digital filters (in Matlab) on hardware platform (FPGA).

- These techniques for designing of digital filters would be simple and optimized.

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